SiC and diamond as radiation hard semiconductor detectors

Annika Lohstroh

Department of Physics, University of Surrey, SEPnet, UK
Email: A.Lohstroh@surrey.ac.uk

Acknowledgements

Surrey University:

P.J. Sellin
S. Gkoumas
A.W. Davies
P. Veeramani
M. Hodgson
P. Bryant
F. Schirru
Yusuf Abubakar

I. Gomez Morilla
G. Grime
C. Jeynes
A. Cansell
M. Browton
A.Simon

CEA (P. Bergonzo, N. Tranchant, C. Deschamps)
ESRF (J. Morse)
P. Edwards (Strathclyde)

Element Six Ltd,
Diamond Detectors Limited
EPSRC/STFC/PPARC
British Council
IAEA (CRP: F11016-CR-2)
AWE

SEPnet
South East Physics Network

Department of Physics ~ 30 academics

Part of he Faculty of Engineering and Physical Sciences (FEPS)

- **Soft condensed matter (SCM)**
- **Astrophysics**
- **Photonics & Semiconductor devices - Advanced Technology in collaboration with electronic engineering**
- **Centre for nuclear and radiation physics (CNRP)**

- Experimental & Theoretical Nuclear Physics
- Medical and Radiation Physics
  - Medical Physics & Imaging
  - Radiation Detector development

2 academics and approx. 12 research students

South East Physics Network

Talk outline

- Basic semiconductor detector operation

- Advantages of wide band gap semiconductors – Low Z Radiation hard materials SiC/D

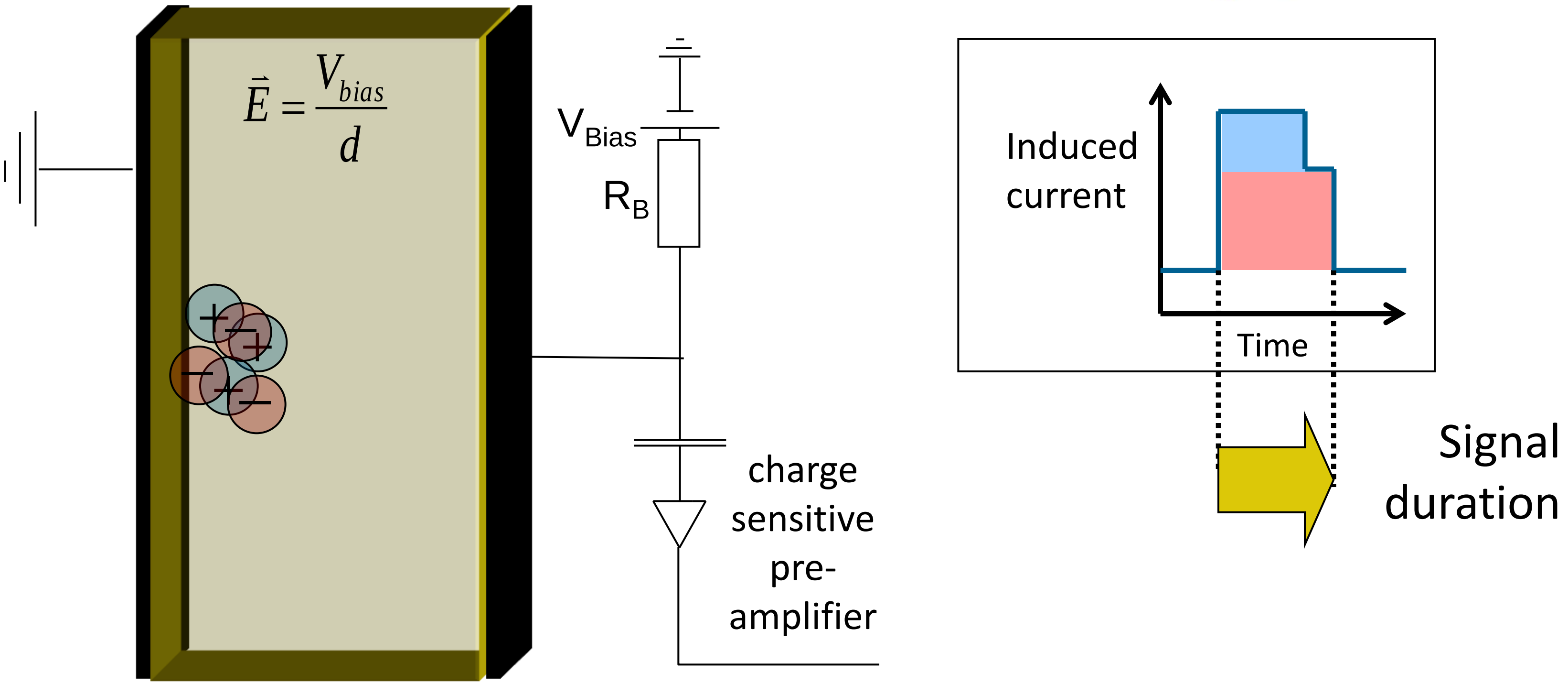
- (General) Effects of Radiation damage on semiconductor detector operation

- Quantifying “radiation hardness”

- Identifying created defects

- Conclusion – Future work

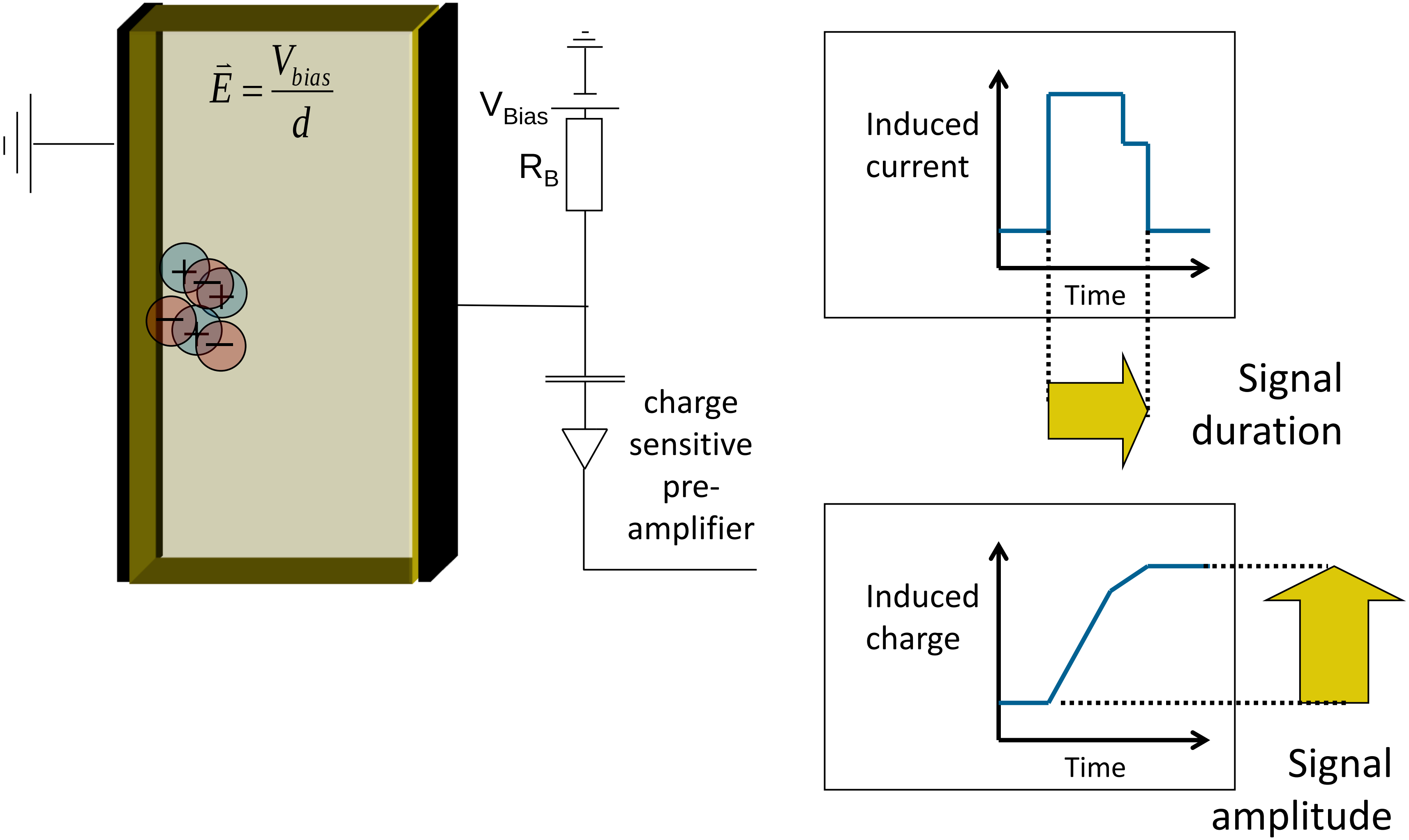
Signal formation



The current signal is induced by the movement of the created charge carriers: the current is proportional to

- the number of carriers → lifetime τ > transit time T_R
- the charge carrier velocity → mobility μ, electric field strength

Signal formation



$$\vec{E} = \frac{V_{bias}}{d}$$

Wide band gap semiconductor materials for room temperature radiation detector application

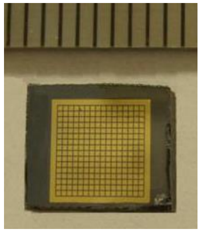
Commercially available PTW chambers based on natural diamonds

Application areas

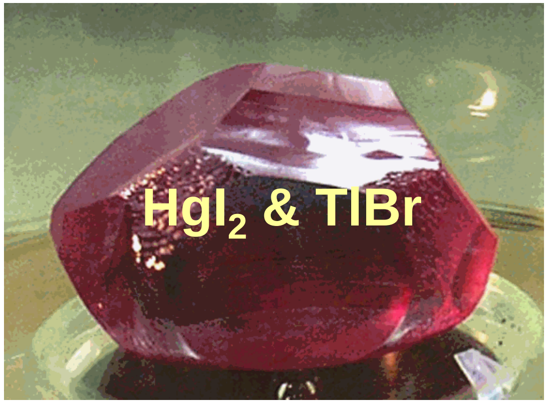
- High energy and nuclear physics
- Neutron detection & monitoring in nuclear industry
- High energy X- and γ-ray detection for medical and security applications
- Photon science/Synchrotron instrumentation
- Medical dosimetry
- High fluence backgrounds and harsh environments
- ....

Two main groups of materials studied

High Z material for X/γ spectroscopy and imaging



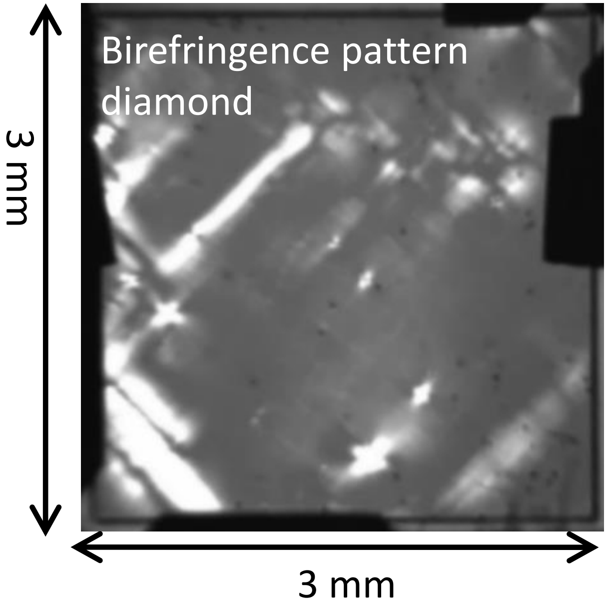
$Cd_xZn_{1-x}Te$



http://www.contech.com/Mercuric_Iodide_Detectors.htm

CdTe CdZnTe
HgI_2 TlBr

Radiation hardness/ Tissue "equivalent" Neutron detection, TOF



Diamond SiC
polymers

Diamond & SiC for sensor applications

Large heat conductance

Low Z (low absorption)

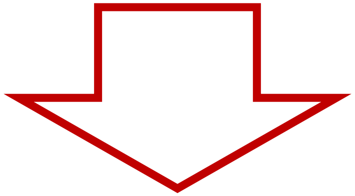
Tissue equivalence*

Wide band gap (solar blind)

Fast charge transport *

Tissue equivalence*

(Radiation) hardness



UV sensor

Neutron detection

(X-ray) Dosimetry

(s)LHC

Beam monitor

*** stronger advantage in diamond compared to SiC**

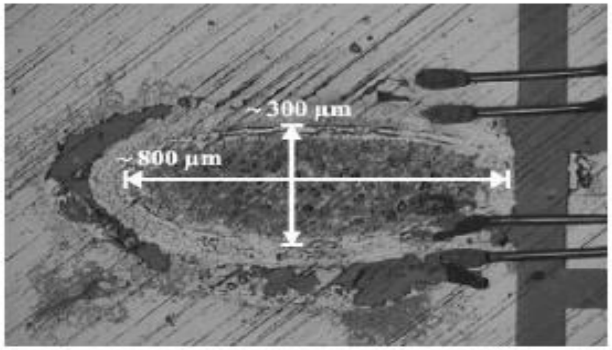
Attractive properties for detector applications (II)

Large band gap
⇒**“solar blind” (UV detection)**
⇒ **(low intrinsic leakage currents)**
high temperature operation

Large heat conductance (5 x copper)

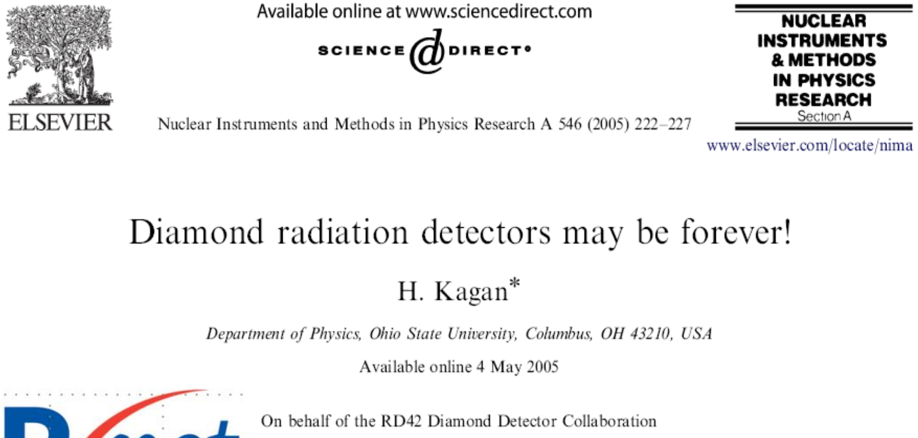
Resiliance
⇒ **Chemically inert**
⇒ **Radiation hardness**

80 µm thick pc CVD diamond detector with Al contact



1 µs bunches of 10^9 of ^{208}Pb^{67+} ions (400 MeV/u =83.2 GeV).
=> Stable signal (in the order of mpere)

J. Bol et al., phys. stat. sol. (a) 204, 9, pp. 2997-3003 (2007)



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Nuclear Instruments and Methods in Physics Research A 546 (2005) 222–227

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
www.elsevier.com/locate/nima

Diamond radiation detectors may be forever!

H. Kagan*

Department of Physics, Ohio State University, Columbus, OH 43210, USA

Available online 4 May 2005

On behalf of the RD42 Diamond Detector Collaboration

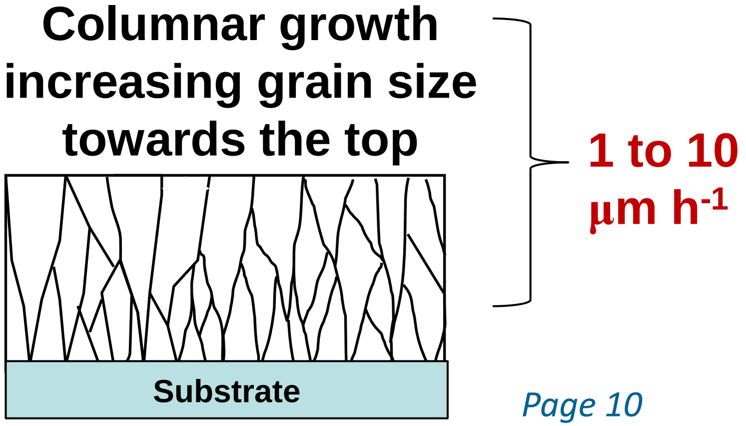
Challenges in the material synthesis

Diamond is meta-stable:

- **High Temperature/High Pressure (HP/HT)** limited volume, purity

- **Chemical vapour deposition (CVD)**
  - Heteroepitaxy (typically polycrystalline – large area possible)

    Diamond on Iridium might be able to provide sufficiently thick, homogenous large areas in the future
  - Homoepitaxy (typically < 1 cm^2 area)



Columnar growth increasing grain size towards the top

1 to 10 $\mu m\ h^{-1}$

Several polytypes of SiC exist

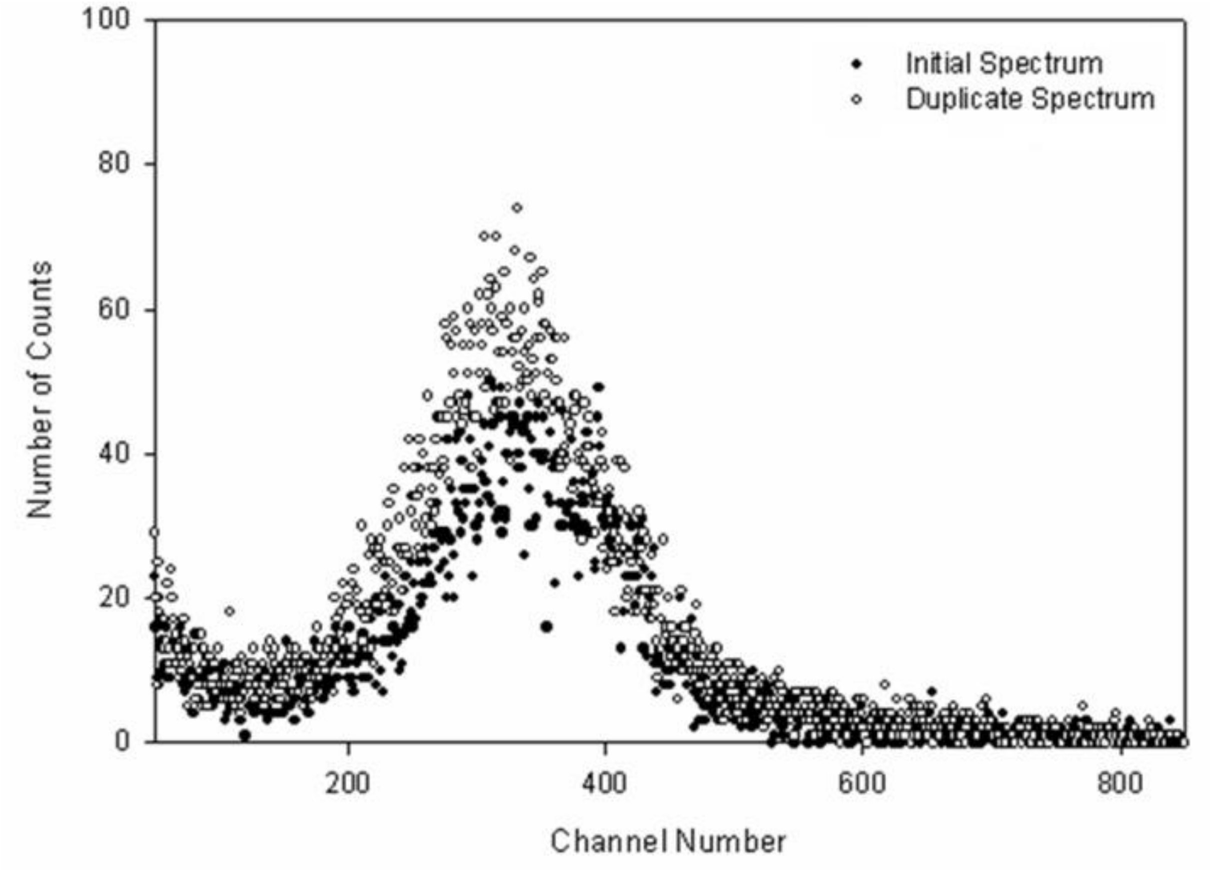
- **Physical Vapour Transport (bulk – single crystal)**

- **Chemical vapour deposition (CVD)**

Common defects

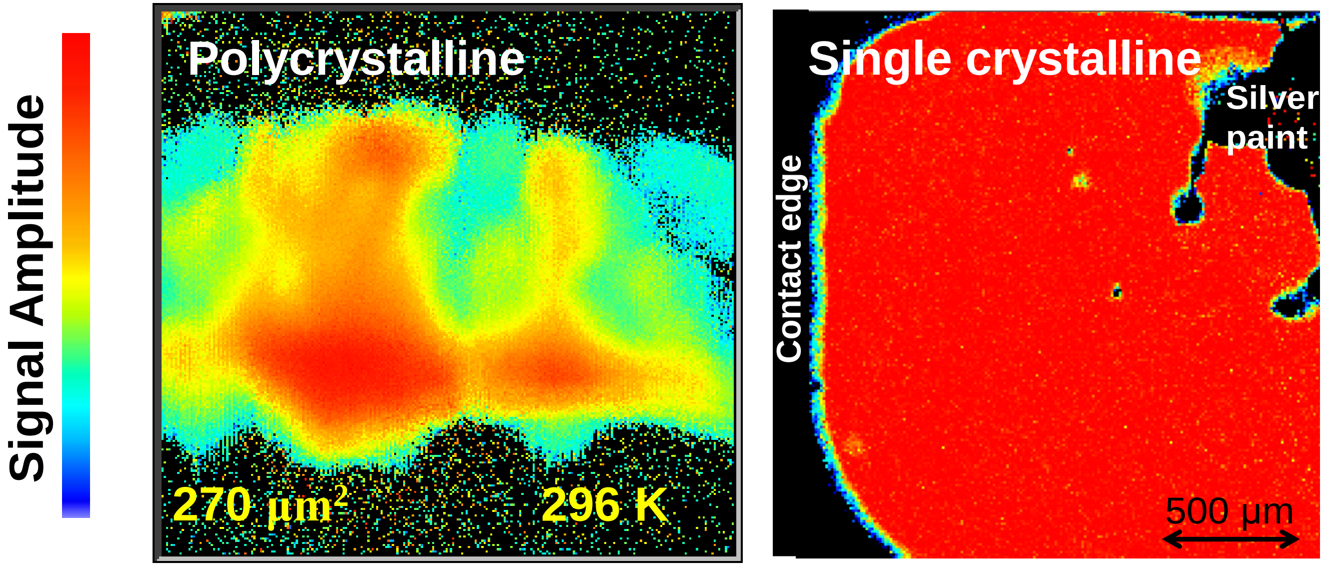
Impurities, Vacancies,
Interstitials
Dislocations
Grain boundaries
Stacking faults
Polytype inclusions

SiC – thick (350 µm) "bulk" material



Bryant et al, IEEE TNS 60(2), pp. 1432 – 1435, 2013

Non-uniform response in polycrystallline material



Electronic grade single crystal detector performance

Energy resolution similar to Silicon

Time resolution, time of flight: 28 ps

See Figure 8 and 9 in M. Pomorski et al. phys. stat. sol. (a) 203 (12), pp. 3152-3160 (2006) DOI: 10.1002/pssa.200671127

See Figure 22 in M.Ciobanu, IEEE TNS 58 (4), pp. 2073-2083 (2011) DOI:10.1109/TNS.2011.2160282

Towards large area single crystals

Images from E. Berdermanet al, 3rd Carat Workshop at GSI, Dec 2011

Heteroepitaxial growth on Iridium – large area substrates possible
Main European player: M. Schreck et al in Augsburg/Germany

For illustrations see:

http://www-carat.gsi.de/CARAT03/CARAT03Talks/Berdermann_CARAT03.pdf

Slide 4 and 14

Continuously improvement in thickness, quality and area with time

Towards more radiation hardness

Images from B. Caylar et al, 1st Adamas Workshop at GSI, Dec 2012

For illustrations used see:

http://www-adamas.gsi.de/ADAMAS01/talks/caylar.pdf

Slide 5 and 19

Several groups have demonstrated working devices:

Full CCE reached at very low applied bias (operate detectors with a 9V battery is possible)

SiC – excellent Schottky diodes for Spectroscopy have been demonstrated

Figure 2 in Ruddy et al, Nucl. Instr. Meth. B 263 (2007) 163-168

doi:10.1016/j.nimb.2007.04.077

High Temperature spectroscopy in epitaxial SiC Schottky diodes developed by RD50)

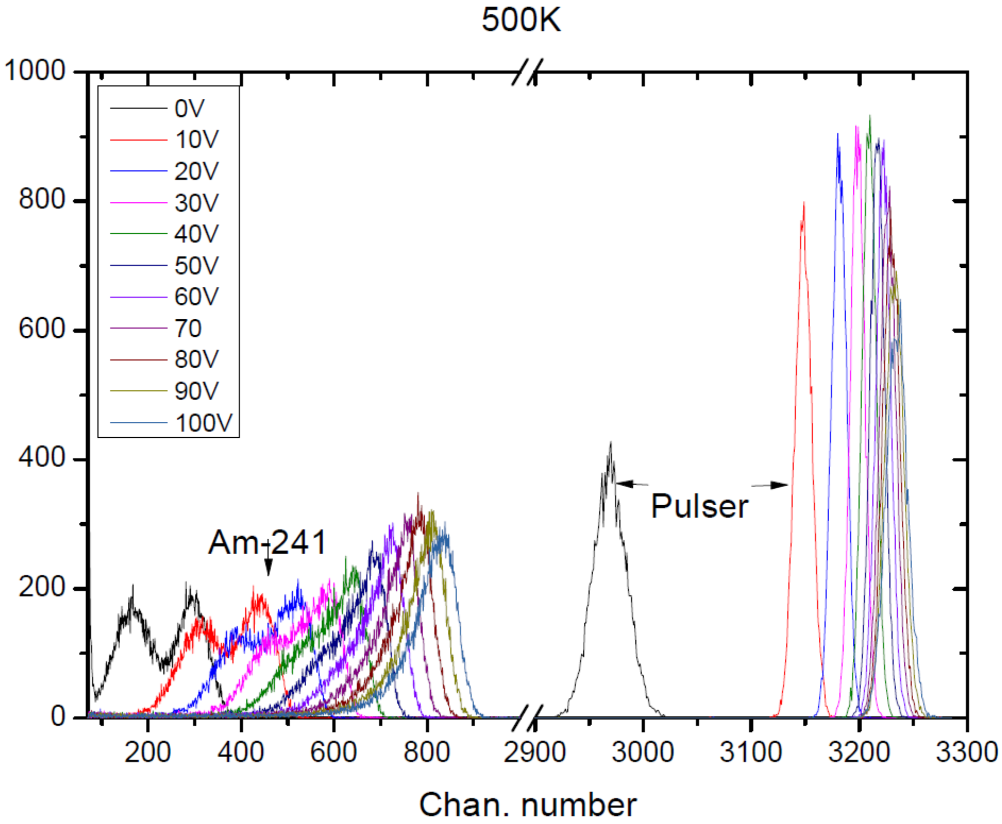
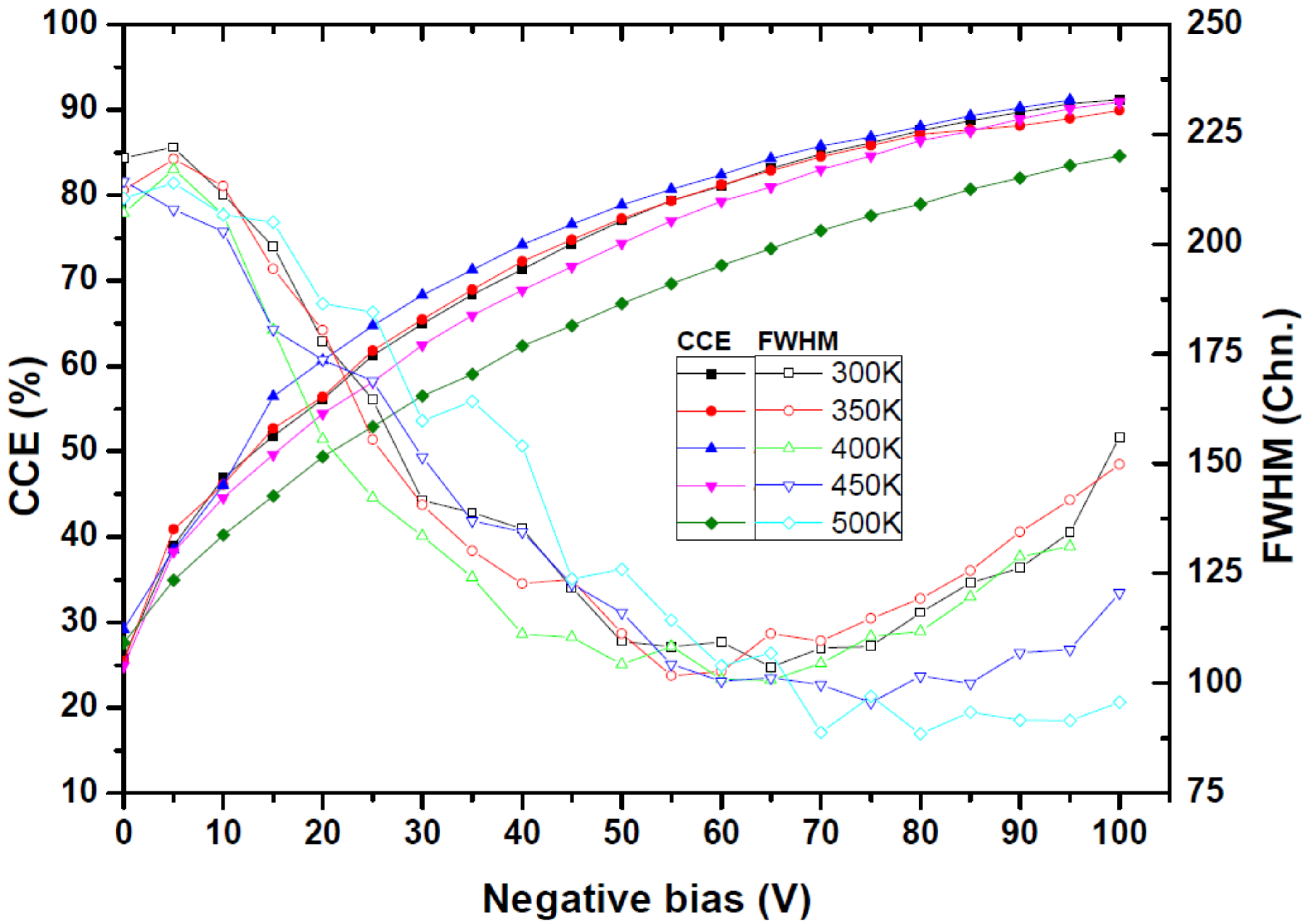


Figure 1 inC. Manfredotti et al., Nucl. Instrum. Meth. A 552 (2005) 131–137
doi:10.1016/j.nima.2005.06.018

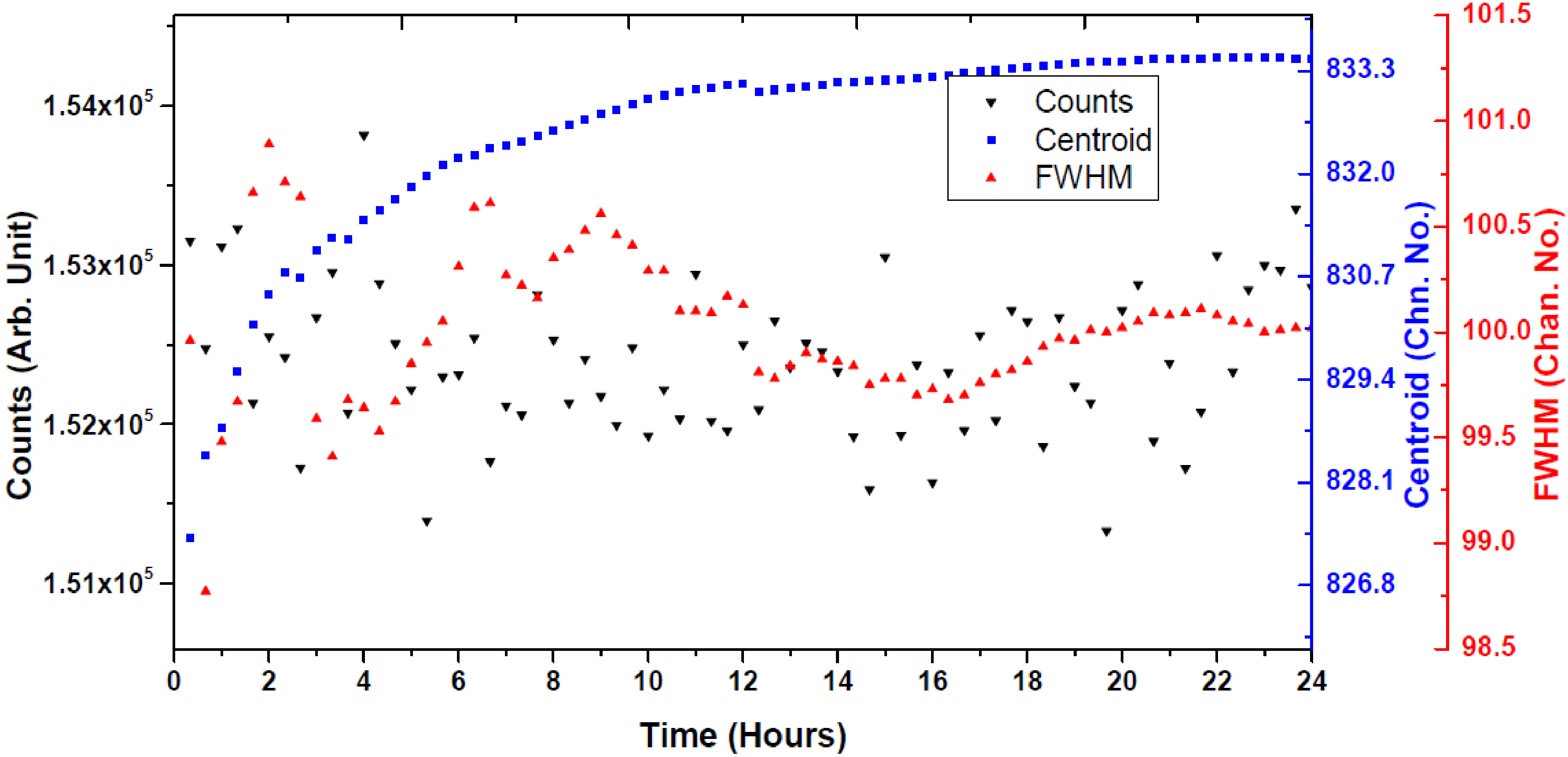
Alpha emission energy spectrum broad with average energy at 5 MeV

(Due to encapsulation of source to be safe to use at elevated Temperature)

High Temperature spectroscopy in SiC



High Temperature spectroscopy in SiC



Stability tests under fast neutron and gamma irradition at room temperature show of epitaxial and bulk SiC samples also show good stability at 4.5 to 18.5 mSv/hour (AmBe Source, Co-60)

Creation of defects due to irradiation

E_K =60 keV

4 fold

Energy transfer to the lattice atoms moves them from a substitutional to an interstitial site:

→ Creation of [$V – C_i$] (Frenkel pair)

Dissociation and diffusion then can lead to many more defect Complexes……

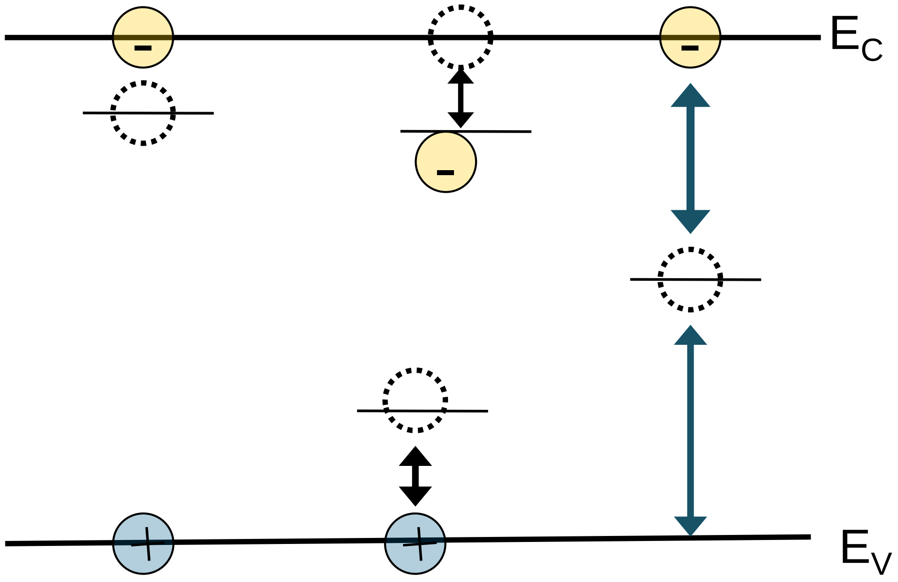
International Journal of Modern Physics C 9, p1x 1998, D. Saada, J. Adler, and R. Kalish

K. Schmetzer, The Journal of Gemmology / 2010 / Volume 32 / No. 1–4

Annealing can change the defect types and concentrations further

Effect of damage on electrical properties

… changes the type/concentration of defects present in the material and hence introduces/removes energy levels in the band gap



- “Close” to E_C / E_V: Dopants
- Near “mid gap”: Recombination centres

Effect of damage on electrical properties

… changes the type/concentration of defects present in the material and hence introduces/removes energy levels in the band gap

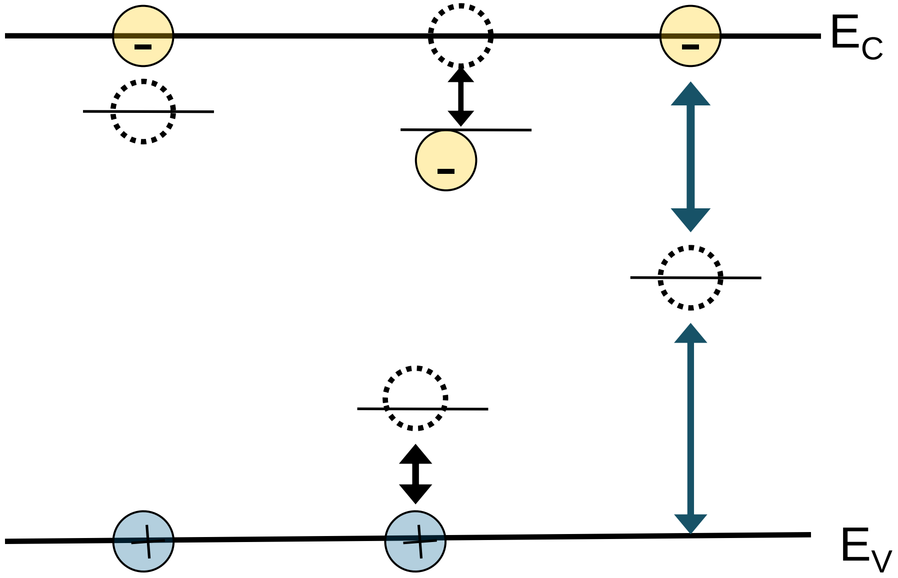
Leakage current:

In an “ideal” intrinsic semiconductor, free charge carrier density is given by

$$n \approx N_C \exp\left(-\frac{E_G}{2k_BT}\right)$$

N_c, density of states in the conduction band ~ 10^{19}cm^{-3}

Large E_G gives lower dark currents, but experimentally “intrinsic” leakage current dominated by free carriers from defect states in the band gap



Effect of damage on electrical properties

- **increase leakage**
  - increase in effective doping

- **reduce leakage**
  - Compensation (reduction in doping)
  - Reduction in carrier life time (recombination)

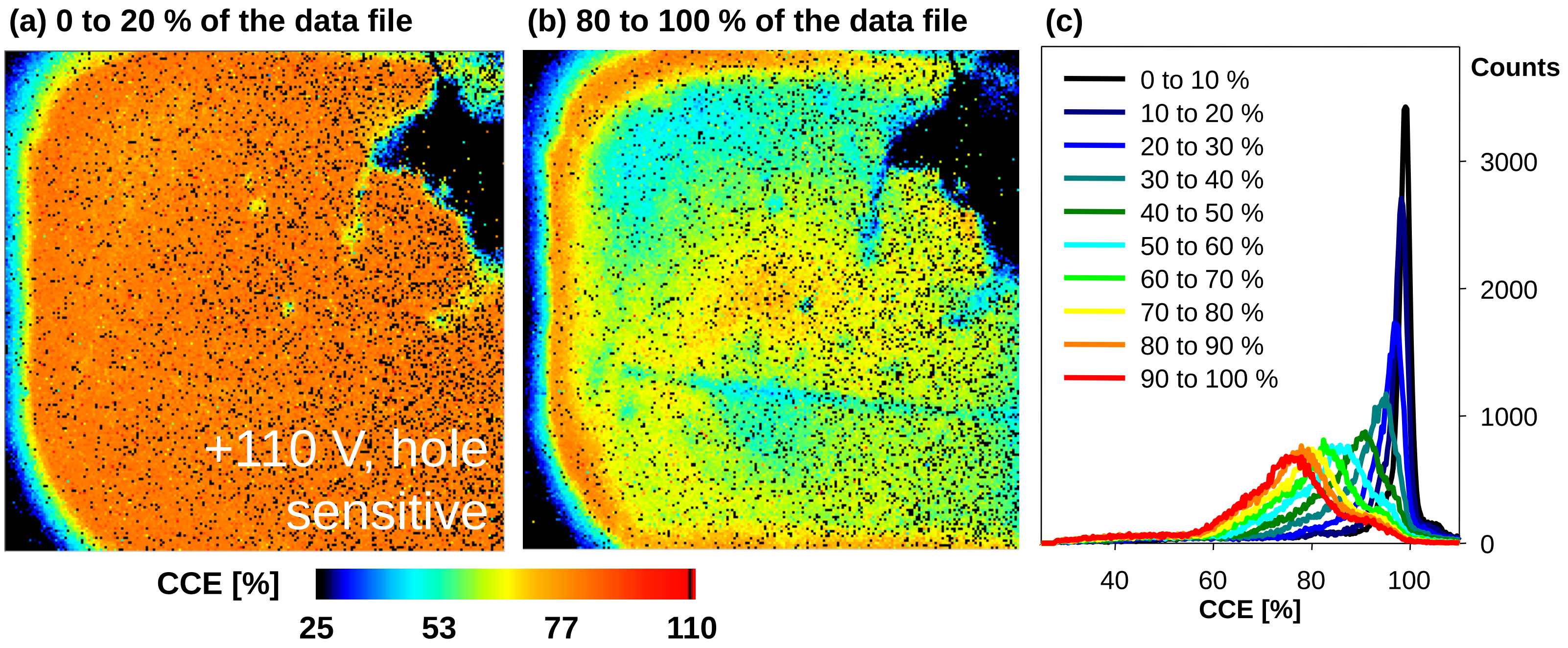
Signal acquisition:

- Reduction in free carrier lifetime – possibly reduced signal
- Trapping/De-trapping – “slower” signal
- Reduction in active thickness (depletion thickness depends on doping in diodes)

Polarisation a contact problem?

<u>Surface and temporary effects:</u>

- “temporary” changes in space charge distribution (polarisation)
- increase in number of occupied traps – increase in lifetime (priming)


(a) 0 to 20 % of the data file

(b) 80 to 100 % of the data file

(c)

+110 V, hole sensitive

Inconsistencies as a function of contacting method also observed by W. DeFerme, Hasselt Diamond Workshop 2009

The challenge of quantifying radiation hardness for detector applications

The NIEL concept – assumes displacement damage cross- section D (MeV mb) – assumes that lifetime scales with # displacements

Seems to work for protons/neutrons > 0.1 GeV

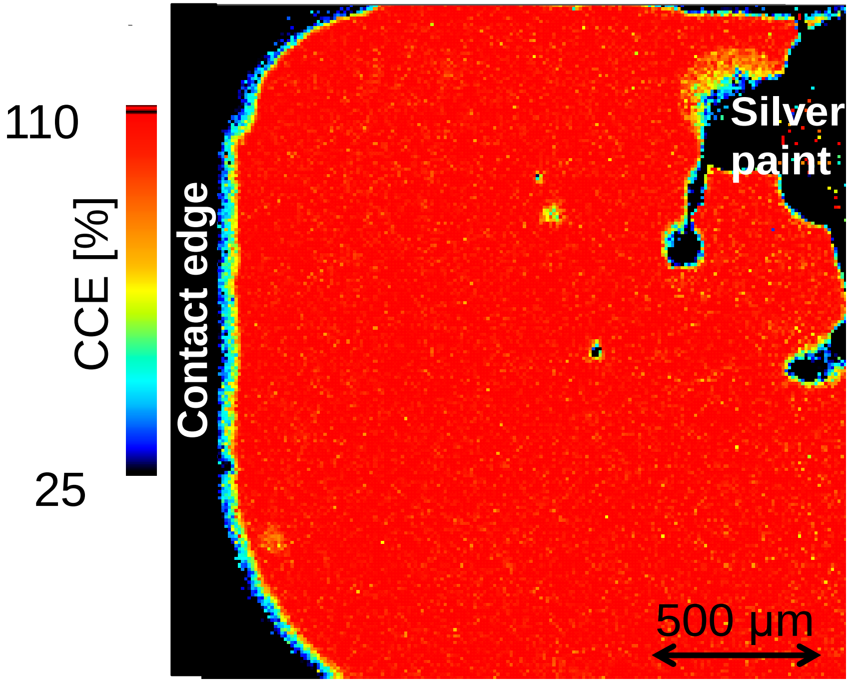
Figure 4 De Boer, phys. stat. sol. (a) 204, No. 9, 3004–3010 (2007)
DOI: 10.1002/pssa.200776327

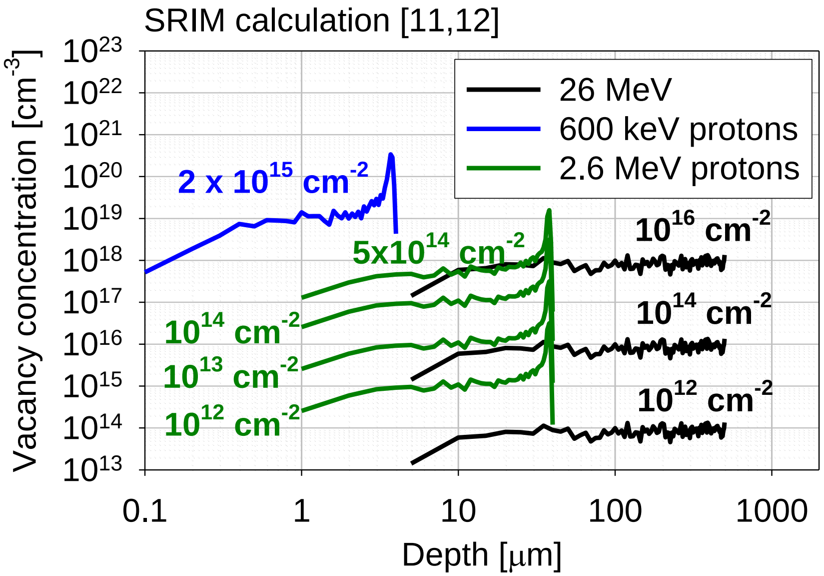
Damaging radiation and probing radiation penetrate through the device thickness.
(26 MeV H^+/ 20 MeV n/ MIPs)

Signal halves after
p: 4.5 (1.5)x10^{14} cm^{-2}
n: 1.3 (3)x10^{15} cm^{-2}

The challenge of quantifying radiation hardness for detector applications

What if the damaging/probing radiation does not penetrate the whole device?



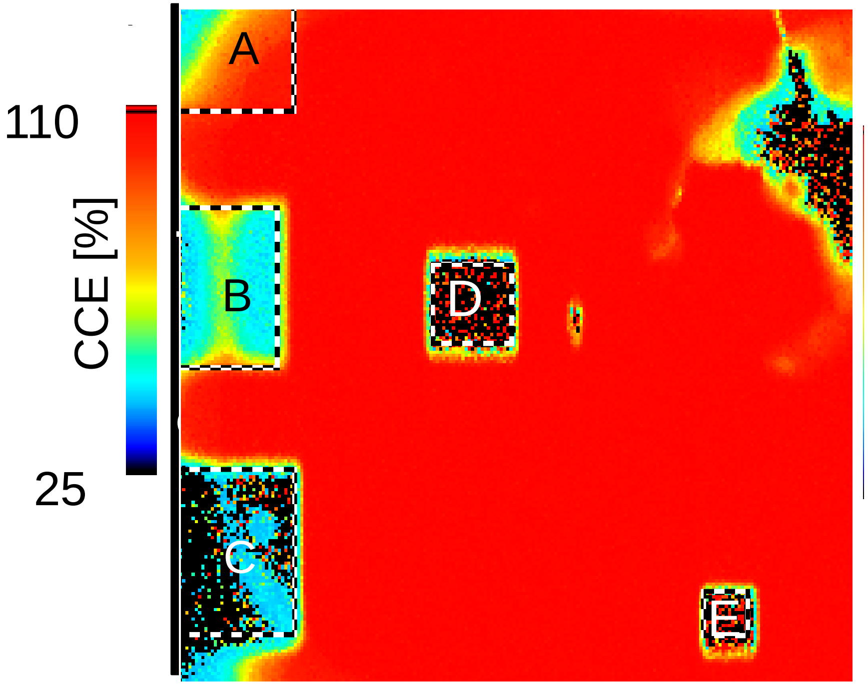


A. Lohstroh et al, phys. stat. sol. (a) 2008, 205(9); p.2211-2215

Damaged area not visible in Raman spectra

The challenge of quantifying radiation hardness for detector applications

What if the damaging/probing radiation does not penetrate the whole device?



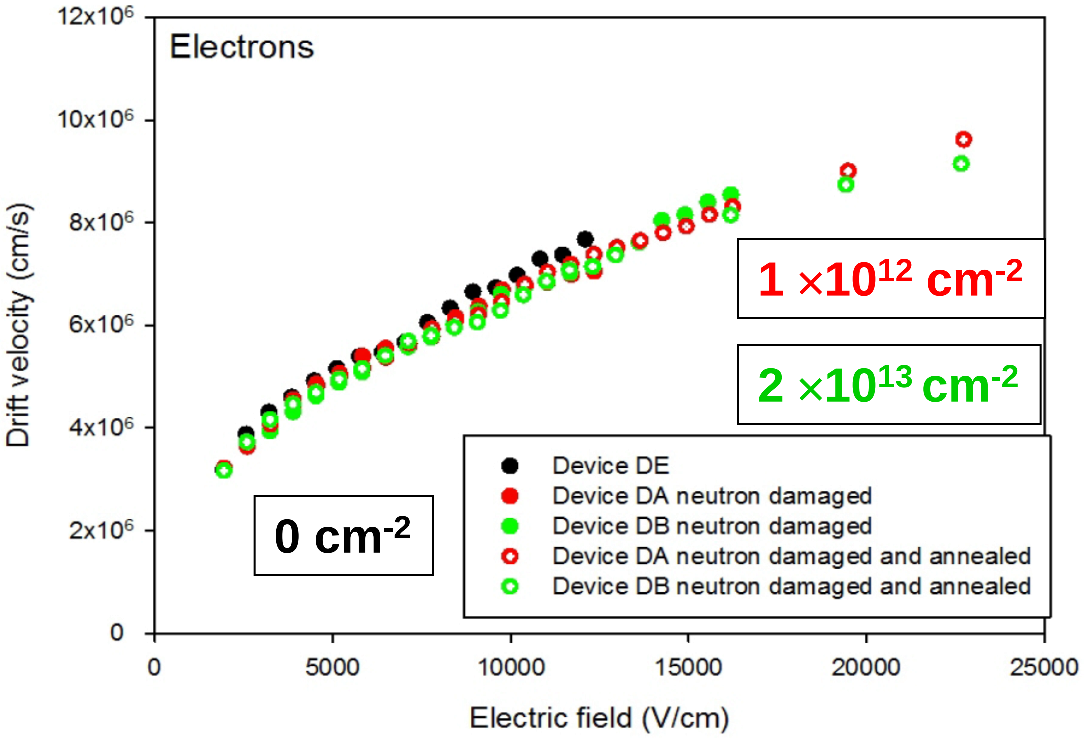
Label	Area [10^{-3} cm^2]	Dose [cm^{-2}]
A	**2.6±0.3**	**(1.1±01)x10^{12}**
B	**2.4±0.3**	**(1.1±01)x10^{13}**
C	**2.6±0.3**	**(1.0±01)x10^{14}**
D	**0.6±0.14**	**(5±1)x10^{14}**
E	**0.18±0.08**	**(1.0±0.4)x10^{15}**
F	**0.05±0.04**	**(5±4)x10^{15}**

A. Lohstroh et al, phys. stat. sol. (a) 2008, 205(9); p.2211-2215

Damaged area not visible in Raman spectra

TOF/TCT measurements …

… confirms that damage does not have a strong effect on mobility compared to lifetime (in Diamond)



1×10^{12} cm^{-2}

2×10^{13} cm^{-2}

0 cm^{-2}

S. Gkoumas, PhD thesis, University of Surrey 2012

$$\mu_0 = (1600 \pm 100)\ \mathrm{cm^2\ V^{-1}\ s^{-1}}$$
$$v_{sat} = (1.20 \pm 0.05)\ \mathrm{V\ cm^{-1}}$$

Introducing a "corrected" Damage factor

- **Assume that trapping probability increases linearly with radiation fluence**
- **Take into account damage profile (e.g. SRIM or other code)**
- **Ionisation profile of probing radiation (e.g. SRIM or other code)**

Z. Pastuovic et al, Proc. of SPIE Vol. 8725 87251A-1

Figure 4,5, 6

doi:10.1117/12.2015541

Works well for "low level damage in Silicon"

=> Needs to be demonstrated in wider range of materials

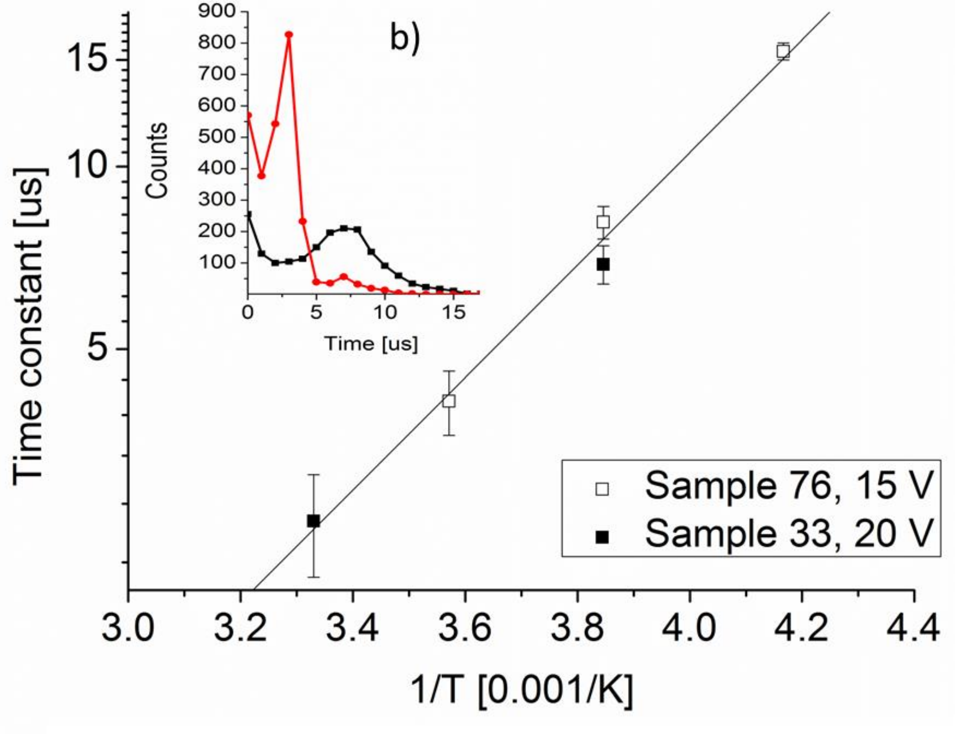
IAEA (CRP: F11016-CR-2)

Identifying defect levels that affect the detector signal

Defect characterisation in semiconductors

- **DLTS** not useful for high resistivity
- **PICTS** light source/limited time scale
- **Luminescence** not quantitative/ cannot see non-radiative defects
- **Optical absorption** detection limits/sample size
- **EPR** sample size, only sensitive to paramagnetic
- **PAS** sample size
- …

Direct observation of damaged detector signals



IAEA (CRP: F11016-CR-2)

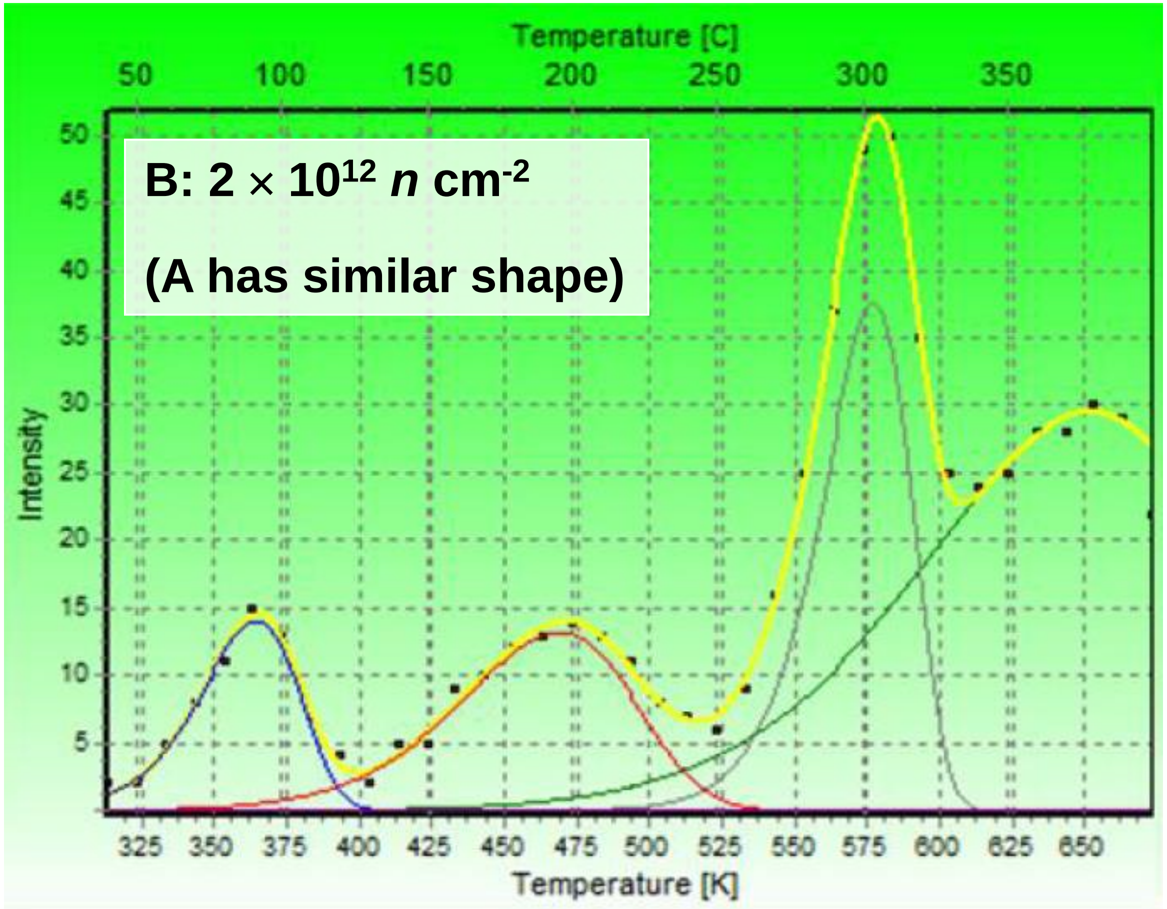
TL – after annealing

20 Gy pre-irradiation – 313 K to 650 K, 10 K/s

$1 \times 10^{12}\ n\ \mathrm{cm}^{-2}$: 0.5 eV
0.6 eV
1.7 eV
0.7 eV

$2 \times 10^{13}\ n\ \mathrm{cm}^{-2}$: 0.6 eV
0.6 eV
1.8 eV
0.6 eV

$1 \times 10^{16}\ n\ \mathrm{cm}^{-2}$: 0.6 eV
0.6 eV
0.8 eV
0.9 eV



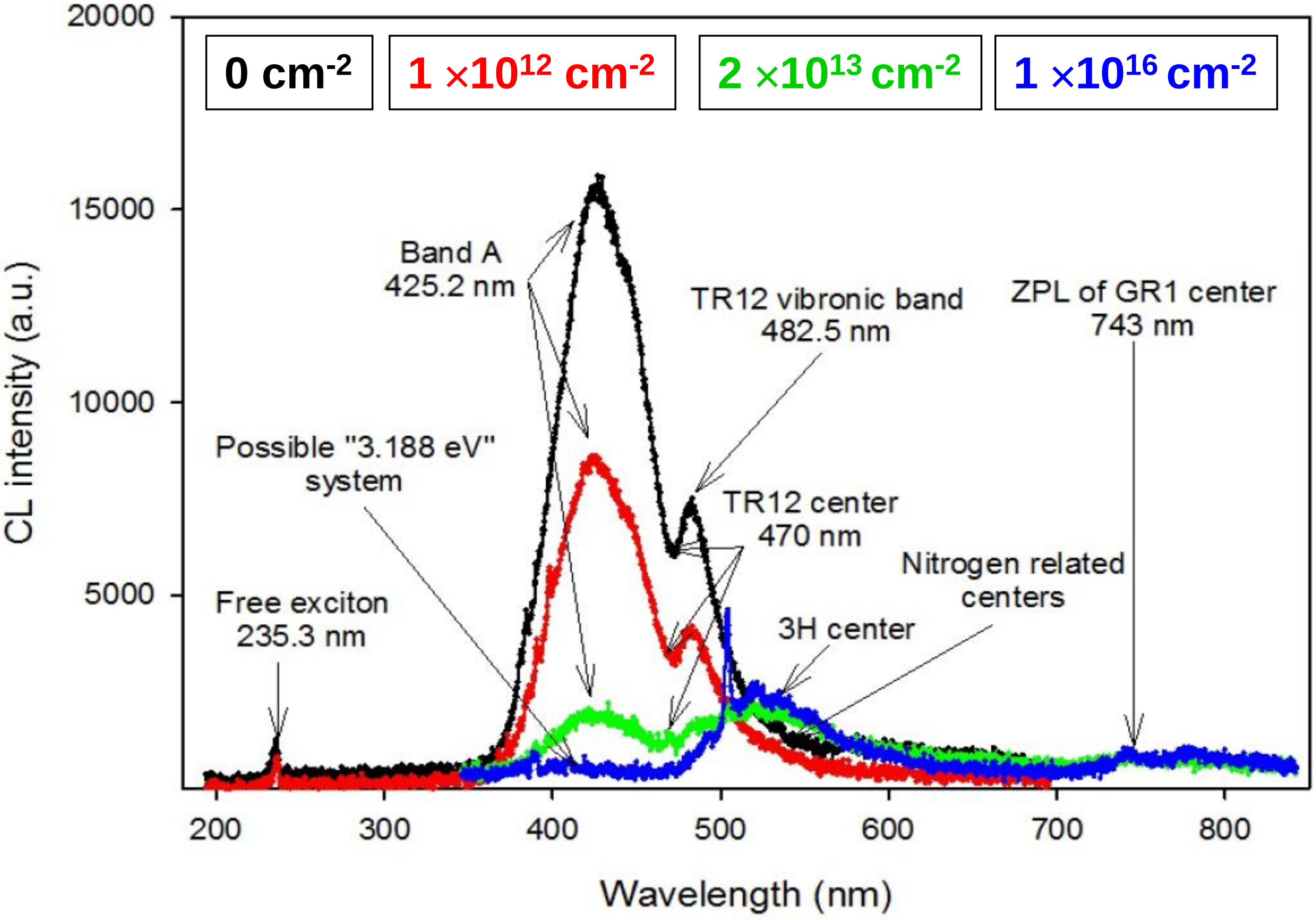
B: $2 \times 10^{12}\ n\ \mathrm{cm}^{-2}$

(A has similar shape)

In pc: 1.8 to 1.9 eV observed by Gonon et al. (APL 70 (1997) 2996-2998) and Benabdesselam et al. (DRM 10 (2001) 2084-2091) (substitutional Nitrogen?)

S. Gkoumas, PhD thesis,
University of Surrey 2012

CL – before annealing

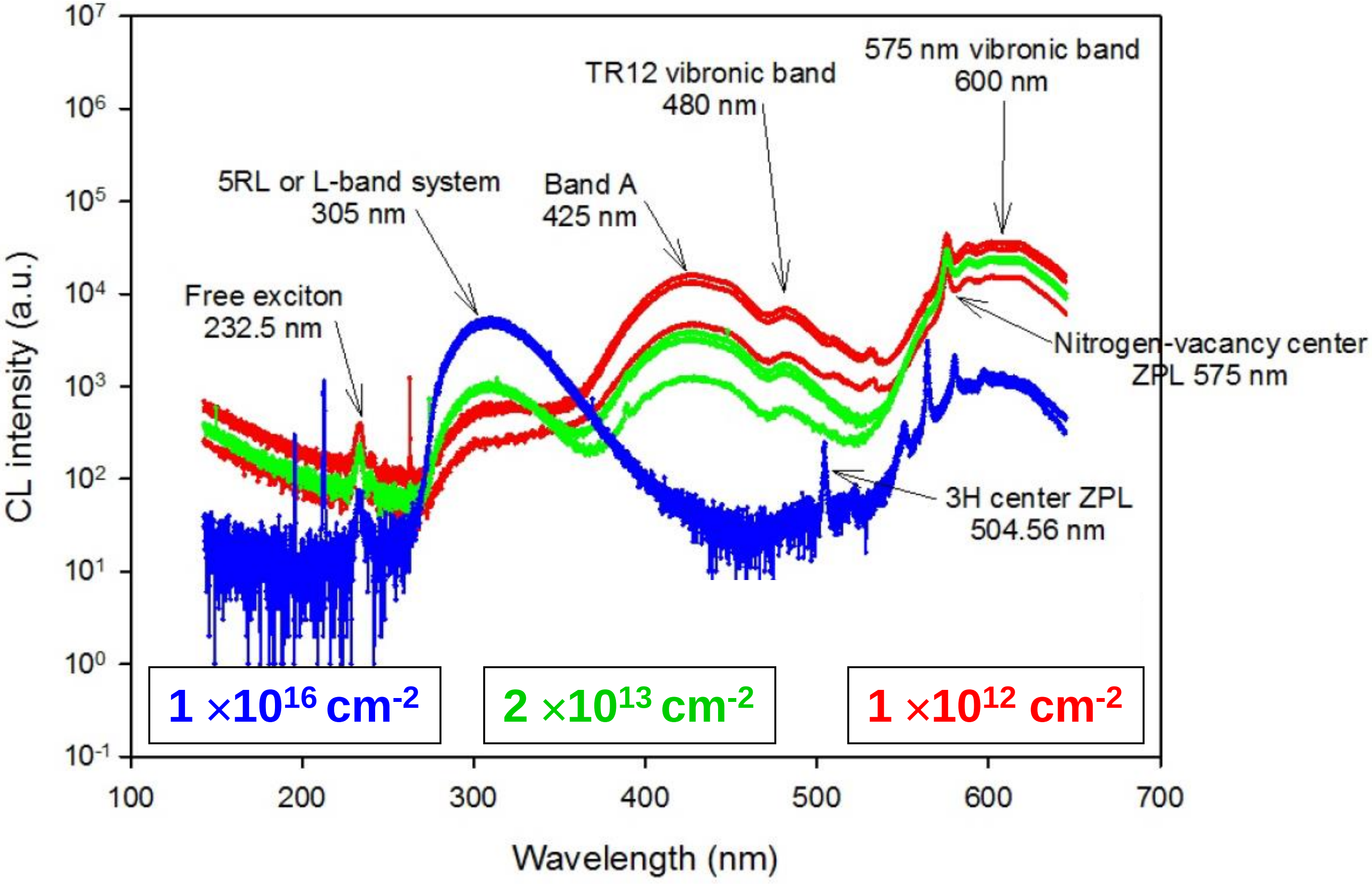


S. Gkoumas, PhD thesis, University of Surrey 2012

3H and "3.188 eV" centre – also seen in neutron irradiation study
Almaviva et al JAPP 106 (2009) 073501

Reference for defect levels: A. M. Zaitsev, Optical Properties of Diamond: A Data Handbook, Springer-Verlag, Berlin – Heidelberg, 2001

CL – after annealing



CL – summary

		Before annealing	After annealing			
λ [nm]	E [eV]	0 ncm^{-2}	A: 1×10^{12} ncm^{-2}	B: 2×10^{13} ncm^{-2}	C: 1×10^{16} ncm^{-2}	
235	5.29	√	√√	√	√	**Free Exiton**
305	4.07					**5RL - self interstitial or L band**
389	3.19					**Known as damage signature**
425	2.92	√	√√	(√) √	(√)	**Band A - dislocations**
470	2.64	√	√			**TR12**
503	2.47				√	**3H - interstitial**
533	2.33	√	√			**N-related**
575	2.16	√	√√	√	√	**$[N\text{-}V]_0$**
741	1.67			(√)	√	**GR1 (single neutral vacancy)**

Conclusion

- Estimating the operational lifetime of detectors needs more understanding of the effects of radiation induced damage on their characteristics – including self annealing

- In wide band gap semiconductors, separating priming/polarisation and structural damage is challenging

- "Radiation hardness" as a material property independent of radiation and probe is not trivial

- Improving our understanding of hardness and defect characteristic with the help of IAEA coordinated research programme

Thank you!

UNIVERSITY OF SURREY

Questions?

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